The U.S. Army Corps of Engineers Field Research Facility: More Than Two Decades of Coastal Research

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Abstract

The Field Research Facility (FRF), located on the Atlantic Ocean in Duck, NC, was established by the U.S. Army Corps of Engineers in 1977 to support the Corps' coastal engineering research requirements. The facility consists of a 560-m- (l,840-ft-) long research pier, a main office building, field support building, and a 40-m- (130-ft-) high observation tower. Since its creation, the FRF has maintained a comprehensive, long-term monitoring program of the coastal ocean including waves, tides, currents, local meteorology, and the concomitant beach response. This monitoring program is supported by a small, highly-skilled field staff and several unique vehicles that permit successful operations in the turbulent surf zone. These capabilities have also supported a series of multiagency multiinvestigator experiments that have led to the Duck beach becoming the best-studied beach in the world. To date, approximately 150 journal articles, 108 reports, and 84 conference proceedings papers have been published using FRF data by more than 200 authors. This paper summarizes the capabilities of the FRF and reviews the impact of its first 23 years of operation.

Introduction

The U.S. Army Corps of Engineers' Field Research Facility (FRF) in Duck, NC, was officially dedicated by Congressman Walter Jones, Sr., in 1980, thereby ushering in a new era of nearshore research and discovery. Since its earlier construction in 1977 (Figure 1), the FRF has provided the Corps and the worldwide coastal research community with the capability of conducting complex and comprehensive nearshore research and engineering studies. Through its long-term measurement program and series of comprehensive multiagency multiinvestigator experiments, the FRF has contributed significantly to understanding the nearshore zone, an active area of the coast included in all shore protection and navigation projects. Because the Duck site is representative of many U.S. coastal locations, FRF data are helping to meet the need for field data to calibrate and verify the accuracy of analytical, numerical, and physical model predictions. Because of the ready availability and high quality of FRF ground-truth data, Duck has also been the site of a wide range of equipment and development efforts, particularly in remote sensing.

History of the FRF

In the 1960s little was known about the dynamics of the surf zone. Except for the classic studies of O'Brien, Shepard, Bascom and others during the Second World War (see Bascom 1987 for insight into these early experiments; Moore and Moore 1991), most field studies of the surf zone were conducted from fishing piers, including several in North Carolina. Coastal scientists and engineers conducting research in the harsh environment of the coastal zone faced particularly difficult data collection problems such as installation of instruments under less than ideal conditions and exposure to a variety of hazards, including storms and hurricanes. Accurate bottom surveys made by individuals wading through the surf zone or by amphibious military craft were extremely difficult or impossible to obtain. Because of these problems in collecting comprehensive and accurate field measurements, the state of the art of coastal engineering was slow to advance.

In response, the concept for a field research facility was proposed in 1963 by Mr. Rudolph Savage, Chief of the Research Division of the Coastal Engineering Research Center (CERC).[3] The recently created CERC was learning how difficult field data collection was through an ambitious wave measurement

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2 Naval Research Laboratory, Stennis Space Center, MS

3 The Coastal Engineering Research Center (CERC) was created by Congress in 1963, replacing the Beach Erosion Board (BEB). In 1997 CERC merged with the Hydraulics Laboratory to create the Coastal and Hydraulics Laboratory (CHL).

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14. ABSTRACT
The Field Research Facil ity (FRF), located on the Atlan tic Ocean in Duck, NC, was estab lished by the U.S. Army Corps of Engi neers in 1977 to sup port the Corps? coastal engineering research require ments. The facil ity con sists of a 560-m- (l,840-ft-) long research pier, a main office build ing, field sup port build ing and a 40-m- (130-ft-) high obser va - tion tower. Since its cre ation, the FRF has main tained a com prehen - sive, long-term mon itoring pro gram of the coastal ocean includ ing waves, tides, cur rents, local mete o - rology, and the con comitant beach response. This mon itoring pro gram is sup ported by a small highly-skilled field staff and sev eral unique vehi cles that permit suc cess - ful oper ations in the tur bulent surf zone. These capa bilities have also supported a series of multiagency multiinvestigator exper iments that have led to the Duck beach becoming the best-studied beach in the world. To date, approx imately 150 journal arti cles, 108 reports, and 84 conference pro ceedings papers have been pub lished using FRF data by more than 200 authors. This paper summarizes the capa bilities of the FRF and reviews the impact of its first 23 years of oper ation.

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Figure 1. Aerial view of the Field Research Facility showing pier, buildings, and observation tower

program. Storms could not be well documented because the piers on which the gauges were mounted were either destroyed or were too shallow to measure unbroken waves. Establishment of the FRF would complement CERC's physical modeling facilities and serve the following functions (Mason 1979):

- Provide a rigid platform from land, across the dunes, beach, and surf zone out to the 6-m (20-ft) water depth from which waves, currents, water levels, and bottom elevations could be measured, especially during severe storms.
- Serve as a permanent base of operations for physical and biological studies of the site, the adjacent sound and ocean region by the Corps, other Federal agencies, universities, and private industry.
- Provide the Corps with field experience and data that would complement laboratory and analytical studies and provide a better understanding of the influence of field conditions on measurements and design practices.
- Provide a field facility for evaluating new instrumentation.

The primary facility would be a concrete and steel pier constructed sufficiently high to be above expected storm waves and surge, and long enough to cross the most active zone of sediment transport. The search for a suitable site considered a large number of criteria including:

- Sand size typical of U.S. coasts and sufficient depth of sand to prevent underlayer exposure.
- Wave climate and storm exposure representative of U.S. coasts.
- Regular offshore bottom topography free of features that may alter the wave climate.
- Tidal range of 0.5 to 2.0 m (1.5 to 6 ft).
- Representative nearshore slope with the 6-m- (18-ft-) depth contour within 600 m (2,000 ft) of shore.
- A straight coastline outside the range of the effects of any significant littoral barrier.
- Control of the surrounding area to avoid interruptions in research programs.
- An adjacent sound or estuary area.
- Availability of commercial power and communication facilities.
- Usually free of fog or cloud cover to allow frequent use of aerial remote sensing.
- A stable coastline (on a time scale of 50 years)
- Natural dunes.

The FRF became a reality through the efforts of Colonel Donald S. McCoy, then commander of CERC (Moore and Moore 1991). Sites all along the eastern coast of the United States were considered and originally a site within the Assateague National Seashore in Maryland was selected. However, the site was changed to Duck, NC, when the National Park Service retracted their endorsement of the project.

Though more remote, the Duck site satisfied all criteria, except possibly the sediment one. Duck beach sands are typically bimodal

comprised of a coarse (~1 mm) fraction with finer (~0.3 mm) sands. Offshore sediments are uniform and fine, decreasing to ~0.125 mm, 1000 m (3,300 ft) from shore.

The Duck site was previously occupied by the U.S. Navy as a target range for pilots operating out of the Oceana Naval Air Station in nearby Virginia. The Navy had recently decommissioned the site and the 176-acre property was transferred to the Corps. Appropriately, research into dune stabilization using vegetation to reduce aeolian movement of sand from uncovering buried ordnance was already being conducted on the site.

Facilities

The FRF facility includes the 560-m- (l,840-ft-) long research pier, a main office building, field support building, and an observation tower (Figure 1). The research pier is a reinforced concrete structure supported on steel pilings spaced 12.2 m (40 ft) apart on center along the pier length, and 4.6 m (l5 ft) apart across the width (Figure 2). The pier deck is 6.1 m (20 ft) wide and extends from behind the dune to a nominal depth of 6 m (20 ft), at a height of 7.6 m (25 ft) above the National Geodetic Vertical Datum of 1929 (NGVD). The influence of the pier on the adjacent bathymetry and processes is a concern examined by Miller et al. (1983) and Elgar et al. (2001). These studies concluded that the pier had an effect that varied with wave and current conditions and distance from the pier.

Located on the pier is the Sensor Insertion System (SIS), added in 1990 (Figure 3). The crane-like SIS can be moved to any location on the pier and is equipped with wave gauges, current meters, and sediment-transport sensors (Miller 2000). It can be operated in 5-m (16-ft) waves and is able to reach 15 to 24 m (50 to 75 ft) out from the pier to minimize the local influence of the pier on the measurements. The SIS was originally developed to measure sediment transport during storms but it has also found use as an ideal diverless-platform to temporarily deploy or test oceanographic sensors.

The main FRF building was completed in 1980 with accommodation for a permanent staff of two and visiting scientists. Originally designed around a central garage to house a planned, but never constructed precursor to the SIS, the main building immediately required modifications to adjust for changes in equipment and a permanent staff of 10. The dining room and bunk rooms were turned into offices, the large garage went through several different configurations until it was converted into offices, an electronics shop, and storage; and the kitchen was conveniently moved into an area that originally held shower stalls. In 1982, a vehicle garage was added to the facility, and in 1991 the garage was expanded to include a classroom, technical library, machine

Figure 2. Concrete abrasion collar being placed over a piling during pier construction. The collars protect the piling from erosion at the sand/water interface

Figure 3. Sensor Insertion System (SIS) with instrumented boom deployed during storm conditions

shop, dive locker, and general work space. The 40-m- (130-ft-) tall climbable observation tower to support video remote sensing observations and to hold radio antennas was added in 1986. With great ceremony, the tower was christened with a bottle of champagne dropped from the top deck, and bets were taken as to whether it would break or not—it did.

The FRF is probably best known for the CRAB or Coastal Research Amphibious Buggy (Birkemeier and Mason 1984). Designed and constructed by the U.S. Army Engineer District, Wilmington, the CRAB arrived at the FRF in 1978 to conduct some of the first surveys of the bathymetry near the pier. At that time it was not tall enough to drive around the pier, and became stuck on occasion trying to go under it. The height of the CRAB was later increased by 3 m (10 ft) to 11 m (35 ft), sufficient to pass around the pier, and it became a permanent part of the FRF in 1981. The CRAB is an aluminum tripod powered by a lightweight diesel engine that drives the variable stroke pump that powers the three hydraulic wheel motors (Figure 4). It is modeled after a similar looking vehicle designed by R.A. Stearn Inc. (Sturgeon Bay, WI) and constructed by Marine Travelift and Engineering for monitoring beach nourishment projects. Though primarily serving as a survey vehicle, the CRAB supports other tasks in the nearshore, such as: instrument deployments and maintenance; sand sampling and vibracoring; cable laying and retrieving; towing instrumented sleds; conducting sensor maintenance, and functioning as a mobile platform for diving operations. Top speed of the CRAB is 3 kph (2 mph) and it can be operated in waves up to 2 m (7 ft) high. Many operations at the FRF have only been possible because of the CRAB. In recognition of the value of the CRAB to surf zone operations, Dutch researchers, after visiting the FRF, have constructed a similar mobile platform, the WESP (http:// www.frw.ruu.nl/fg/wesp.html).

Two reconditioned LARC-V (Lighter Amphibious Resupply Cargo) vehicles support operations in deeper water or remote from the FRF. Originally built for the U.S. Army to transport cargo between ships and land, these vehicles support diving operations; tow sidescan and sub-bottom seismic instruments; lay and retrieve cables; and deploy and maintain buoys and instruments. One LARC has been converted from the original mechanical drive to hydraulic drive for greater speed and reliability. It has also been equipped

Figure 4. Coastal Research Amphibious Buggy (CRAB) preparing to deploy Naval Postgraduate School instrumented sled during DUCK94 experiment

with a cabin and AC power to support data collection and survey work (Figure 5).

Personnel

The FRF staff includes three scientists, one engineer, two computer specialists, two civil engineering technicians, one equipment specialist, two electrical technicians, and an office administrator. They are well known for their expertise in conducting coastal field research and collectively have nearly 200 years of experience conducting experiments at the FRF and elsewhere. Six of the original 10 staff members[1] (Figure 6) are still working at the FRF, and four of the current staff began work in 1985 or 1986[2]. Part of the attraction of working at the FRF is the lack of a usual routine. Every staff member has multiple responsibilities, and every day is different–from rescuing boats at sea, to preparing the facility for hurricane evacuation or an invasion of scientists, to righting the CRAB after it turned over (only once, October 1987). In addition to conducting their own research, the staff also helps visiting scientists plan their experiments at the facility. Through their intimate contact with the environment, the staff has a unique sense of the conditions to expect and they have the knowledge of how to successfully deploy instruments in the surf zone so they survive.

Measurement Program

Central to all studies at the FRF are the long-term measurements that began in 1977 (Miller 1980). This program has evolved with the addition of new instruments and collection techniques. Measurements currently being made include:

- Wave height, period, and direction at 8- and 16-m (26- and 52-ft) depths;

1 Eugene Bichner, William Birkemeier, William Grogg, Michael Leffler, Carl Miller, Raymond Townsend

2 Clifford Baron, Kent Hathaway, Charles Long, Brian Scarborough

Figure 5. One of the Field Research Facility s Lighter Amphibious Resupply Cargo (LARC-V) vehicles conducting a bathymetric survey

Figure 6. Original Field Research Facility staff. Left to right (bottom row): Bill Grogg, Harriet Klein, Carl Miller (seated), Curtis Mason, Gene Bichner, and Mike Leffler. (Top row): William Birkemeier and Ray Townsend

- Wave height and period (three points along the pier);
- Vertical current profile at 8-m (26-ft) depth;
- Water level (four locations and National Oceanic and Atmospheric Administration/National Ocean Service primary tide station);
- Water temperature, visibility, salinity (surface and daily profile);
- Wind speed and direction;
- Atmospheric pressure, air temperature, humidity, precipitation;
- Bathymetry (biweekly);
- Annual aerial photography; hourly video imagery

Wave measurements have always been a primary interest. Buoy 44014 maintained by the NOAA/National Data Buoy Center (NDBC) provides directional wave measurements 94 km (58 mi) from shore in 47-m (150-ft) water depth, near the edge of the continental shelf. A Datawell® Directional Waverider Buoy measures nonbreaking wave conditions 4 km (2.5 mi) offshore in 16 m (52 ft) of water. Further inshore, the full directional wave spectrum is determined from the FRF's 8-m Directional Wave Array composed of 16 bottom-mounted pressure sensors arranged in a shore-parallel, shore-normal cross (Long and Oltman-Shay 1991). This array was deployed in 1986 and designed by Dr. Joan Oltman-Shay with the capability to resolve a unidirectional wave train to within 5 deg and two wave trains at the same frequency if they differ by 15 deg in direction. It may be the longest running high-resolution directional wave gauge in the world (Figure 7).

In order to maintain real-time observations, most FRF instruments are wired to the main building via a network of armored cables. Although the data from some sensors are collected digitally, most sensors, including the 8-m Directional Wave Array sensors, provide a continuous analog voltage output that is digitized at the computer. A Global Positioning System (GPS) time-server controls the digitization so that the phase relationship between sensors can be precisely measured. Originally, data from all analog sensors were recorded at a 2-Hz sample rate for 34 min every 6 hr, except during storms when data were recorded hourly. Improvements in data collection computers and storage capacity allowed for near continuous data collection starting in 1987. Raw time series, computed statistics and spectra are archived for each sensor and collection period.

Instrument observations are supplemented by a daily series of visual observations of parameters like cloud cover, air and water visibility, breaker type, alongshore surface currents, surf zone width, and rip current presence.

A NOAA/National Ocean Service (NOS) primary tide station (number 865-1370), located at the seaward end of the pier collects water-level data every 6 min. NOS has carefully monitored and maintained the tide gauge since installation in 1977 and, as a result, an excellent record of sea level rise, and water-level variation, has been obtained. During the period, NOS converted from their traditional punch paper tape measuring system to their next generation water-level station, based largely on development and performance tests

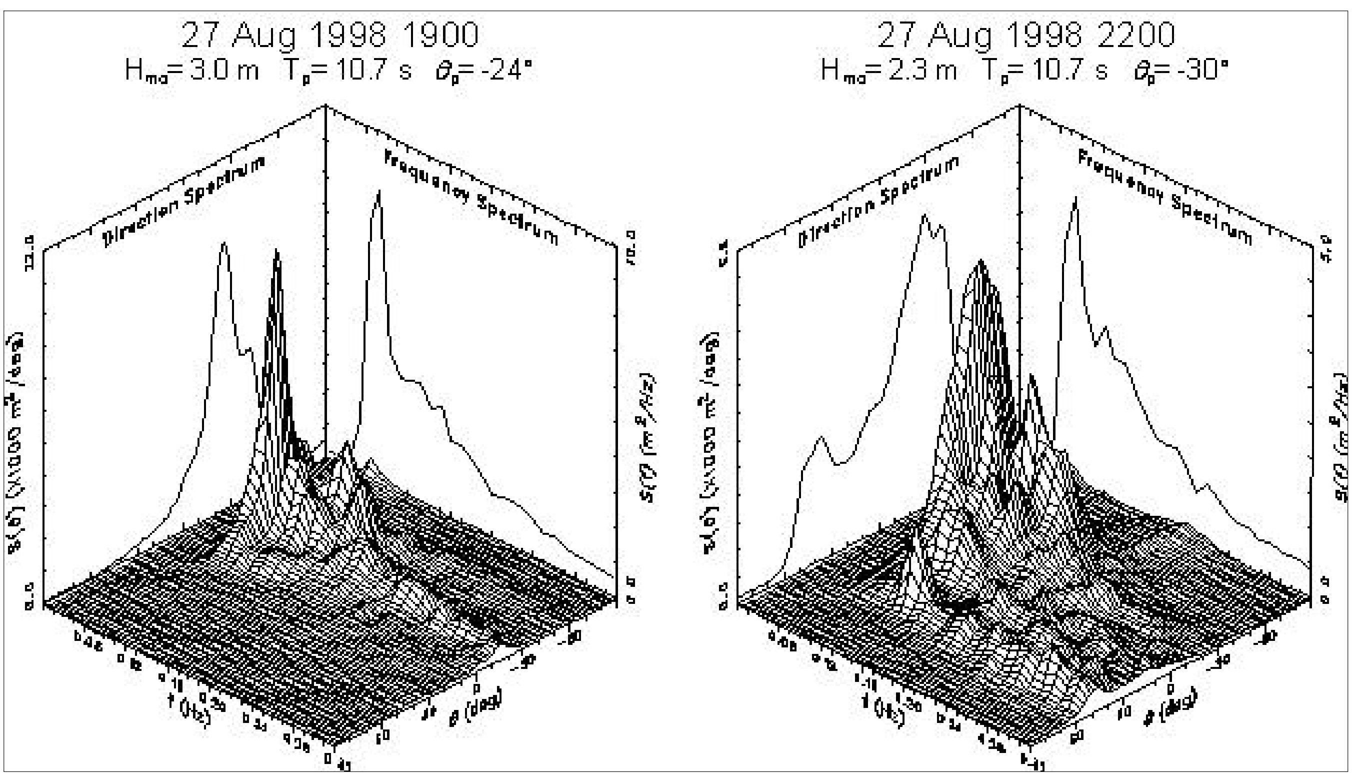

Figure 7. Directional wave spectra collected at the 8-m Directional Wave Array during the passage of Hurricane Bonnie. These data show the significant and rapid changes in the distribution of wave energy reaching the beach

conducted at the FRF. In 1995, NDBC, in cooperation with the FRF, added a permanent Coastal-Marine Automated Network (C-MAN) weather station to the end of the pier as part of a new Ocean Sensor Test Facility for the long-term testing of oceanographic sensors deployed by the Corps or on NDBC's ocean buoys (Woody et al. 1997).

Equally important to the FRF measurement responsibilities is the surveying program using the CRAB to obtain centimeter-accurate measurements through the breaker zone and across the inner shoreface. Four profile lines extending seaward to the 9-m (30-ft) depth contour are surveyed biweekly, and a region 1 km by 1 km centered on the pier is surveyed monthly. The program has benefited from advances in surveying technology through the evolution of four different systems. Early surveys used a surveying level to read a large stadia board mounted on the back of the CRAB. Handwritten notes, weather, biting flies, and reading errors made these data error prone. The level was soon replaced with a Zeiss Elta-2s electronic surveying system, (Birkemeier and Mason 1984). With the Elta-2s, a typical survey of 50 points could be conducted in about 45 min with an accuracy of 3 cm horizontally and vertically.

In 1990, the Elta-2s was replaced with a Geodimeter 140-T self-tracking total station capable of following the CRAB as it moved and acquiring data every second. For the first time, sufficient data points were obtained to fully define the curves and shapes of the nearshore. In fact, some of the earliest evidence of mega-ripples was observed even with the large wheel size of the CRAB. Because the Zeiss and Geodimeter instruments are both range-azimuth systems, their accuracy decreases with distance from the instrument, and they are therefore least accurate at the offshore extent of the surveys, where changes are typically small but can be significant. This problem was resolved in 1996 with the adoption of a Real-Time Kinematic (RTK) GPS system. This system has produced the most consistently accurate data to date and has the added advantage of requiring only a single operator to drive the CRAB and collect the data. By combining the RTK GPS system with a digital echosounder and using the LARC as a platform, the surveys can now be extended into deeper water while maintaining nearly the same accuracy.

The surveys are not frequent enough to capture the dynamic nature of the beach and inner sand bar zone (changes in the foreshore profile of up to 0.8 m have been observed over a single tidal cycle, Holland and Puleo (in preparation)). This region is monitored remotely with video cameras mounted on the observation tower using techniques originally developed by Dr. Robert Holman of Oregon State University. Daily images from a single camera began to be collected in 1986. Today the images from eight cameras are obtained hourly and used to create rectified mosaic images, equivalent to a vertical aerial photograph, for a 2-km (1.2-mile) stretch of coastline, centered on the research pier.

Experiments

To fully utilize the unique potential of the facility and to obtain as many benefits to the Corps and the nation as possible, non-Corps use of the facility and its data has always been encouraged. This policy has led to one of the most productive accomplishments of the FRF, serving as a site for cooperative experiments where resources (funds, labor, instruments, and data) are pooled to investigate complex coastal processes. A sequence of such studies has been conducted at the FRF resulting in a wealth of new coastal knowledge. In addition, these experiments have also created a core group of sponsors (U.S. Army Corps of Engineers, Office of Naval Research, and the U.S. Geological Survey) and researchers who have helped to establish the FRF as a premier research facility.

In l978, DUCK-X brought together 24 participants to evaluate the use of remote sensing for coastal studies, particularly the capabilities of the SEASAT-A satellite. Ground truth data from the FRF proved extremely useful in verifying synthetic aperture radar images sent from the satellite. The Atlantic Remote Sensing Land and Ocean Experiment (ARSLOE) followed in October l980, and included 3l U.S. participants and four foreign researchers. In addition to evaluating remote sensing techniques, wave transformation theories were tested and directional wave measuring systems evaluated (Baer and Vincent 1983).

In the fall of l98l, A Shoreface EXperiment (ASEX) brought several investigators to the FRF to determine the spatial and temporal variability in sediment characteristics, and to relate changes in these characteristics to hydrodynamic processes. This was the first experiment to make extensive use of the CRAB both to survey several cross-shore profiles and to collect a unique series of cross-shore vibracores. Though ASEX included only limited monitoring of morphology and surf zone dynamics, the observations foreshadowed the focus of the following experiments: the complex interaction between hydrodynamics and sediment related processes including morphology change. ASEX was the first of many Duck experiments that Dr. Asbury Sallenger (U.S. Geological Survey) participated in. ASEX was unique in being the only experiment held south of the pier.

It was during ASEX that plans developed for DUCK82 held in the fall of l982 (Mason et al. 1985). FRF scientists and researchers from the U.S. Geological Survey, and Oregon State University conducted a comprehensive month-long study of nearshore processes and morphological change to test models of crescentic sandbar generation (Bowen and Inman 1971). Movie cameras, current meters and wave gauges on the pier, a mobile-instrumented sled and the CRAB were used to collect wave, current, and bathymetric data. It was during DUCK82 that Dr. Robert Holman from Oregon State University began his long relationship with the FRF, bringing his remote

sensing techniques and students to Duck.

The DUCK82 experiment began to define the format and logistics of the experiments that followed. In each, the CRAB was used to water-jet precisely located long pipes or pipe frames into the bottom to support the instruments which were cabled back to collecting systems on shore. Typically the number of instruments was thought to be sufficient, based on the understanding of the dominant processes at the time. As the understanding of the processes improved, the number of instrument locations or nodes and the number of instruments at each node increased (Table 1). Instruments were deployed during the mild conditions of late summer in order to be ready to measure the changes caused by the first fall storms of September or October. Instruments in the surf zone require a high level of attention and maintenance. Therefore, the experiments generally lasted only a few weeks to two months to obtain observations under a range of conditions including storms and to have sufficient time to remove the instruments before winter weather set in. Surveys by the CRAB provided frequent updates of the morphology surrounding the instruments. As the experiments became larger and more complex, one key to their success was the developing experience being gained by the FRF and by repeating participants.

Table 1. Instrument Nodes During the Duck Experiments

Experiment	Instrument Nodes[1]
ASEX	0, instrumented sled
DUCK82	7, instrumented sled
DUCK85	17
SUPERDUCK	30, instrumented sled
DELILAH	19, instrumented sled
DUCK94	41, instrumented sled
SandyDuck	105, instrumented sled

[1] Nodes held one or multiple instruments

The DUCK82 experiment was also a landmark in revealing both the importance of sandbar morphology to nearshore dynamics and the incredible speed and complexity at which sandbars evolve during a storm. Because of the circulation associated with the development of migrating rip channels, adjacent profile lines showed opposite trends with offshore bar migration on one, and accretion on the other. Since the cross-shore focus of DUCK82 did not fully resolve this complexity, the DUCK85 experiment was planned with more frequent surveys and a larger array of instruments. DUCK85 differed somewhat by having a separate mild wave phase in September focussing on sediment-transport measurements (Figure 8), and a storm wave phase in October that provided some of the best quantitative data on the rapid changes that occur during storms (Mason et al. 1987). In fact, the CRAB surveys during DUCK85 uniquely captured the initial, and subtle, development of a rip current through a linear sand bar (Howd and Birkemeier 1987). DUCK85 and the experiments that followed provided training opportunities for Corps office staff. During DUCK85, more than 15 District engineers and scientists

Figure 8. DUCK85 sediment transport experiment, directed by Dr. Nicholas Kraus (CHL). The researchers are tending sediment traps facing into the longshore current which is being measured by the two current meters located to their right. Further to the right, the line of photopoles was observed by movie cameras to measure wave conditions

participated for 2 weeks each. For the surveyors and CRAB operators, DUCK85 was also noteworthy as the first and only experiment where the CRAB was operated through the night. It was quickly learned that the added data did not justify the extraordinary demand on the drivers.

DUCK85 was designed as a preliminary experiment to *SUPERDUCK* in 1986, which again included a morphologic and sediment transport component, and a hydrodynamic component, this time including a 509-m (1670-ft) longshore linear array of electromagnetic current meters (Crowson et al. 1988; Birkemeier et al. 1989). The primary purpose of this array had been to measure the dynamics of edge waves on a barred beach profile, a natural extension of edge wave work on unbarred California beaches (Oltman-Shay and Guza 1987). While edge waves were indeed observed, the most startling result of SUPERDUCK was the discovery of shear waves, large fluctuations in what should have been steady longshore currents (Oltman-Shay, Howd, and Birkemeier 1989). SUPERDUCK also saw the first appearance of Dr. Edward Thornton of the Naval Postgraduate School, an FRF experiment regular, collecting data from his first mobile instrumented sled.

The 1990 DELILAH experiment was essentially an experiment of opportunity, providing an inshore companion to SAMSON, a land and ocean experiment into the causes and importance of ocean bottom microseisms. Planning was compressed into the available 9-month preparation period and the focus was placed on hydrodynamics of the newly discovered shear waves and their relationship to the longshore current profile. Cross-shore and longshore arrays measured waves, currents, and swash dynamics (Birkemeier et al. 1997). These measurements also confirmed that, on a barred beach, the peak in the longshore current occurs over the nearshore trough, not over the bar crest as was predicted by theory at the time. The importance of large mega-ripples to sediment movement was also observed. DELILAH saw Dr. Robert Guza of the Scripps Institution of Oceanography, and Dr. Steven Elgar, now at the Woods Hole Oceanographic Institute, join the ranks of experiment regulars.

The hydrodynamic success of DELILAH, and the need for more detailed information about sediment transport and morphologic evolution led to a plan for two additional field experiments with added components to resolve sediment transport and morphologic evolution at bed form scales from ripples to nearshore bars. The first, DUCK94 (Birkemeier and Thornton 1994), was intended as a test run for the new instrumentation, more formal organization, and more complicated logistics to be exercised during the second experiment, SandyDuck '97. DUCK94 was held during August and October 1994 to take advantage of the synergy offered by the National Science Foundation's Coastal Ocean Processes (CoOP) experiment (Butman 1994), being conducted at the FRF during that time. DUCK94 also saw the first participation by the Canadian research group of Drs. Tony Bowen and Alex Hay and their introduction of scanning sonars technologies to bed form studies. During these two experiments, hundreds of sensors and instruments were deployed in the surf zone, from instrumented sleds pulled offshore, from the pier, and from the observation tower. The centerpiece of DUCK94 was a primary cross-shore array of instruments that included wave gauges, current meters, and acoustic altimeters to measure real-time bed level changes (Figure 9). Additional instruments measured suspended sediments, bottom bedforms, and other parameters (Birkemeier, Long, and Hathaway 1997). The success of the DUCK94 array led to the larger spatial array deployed during SandyDuck (see Table 1). Both experiments benefited from the involvement of a large segment of the North American nearshore research community in the initial planning of the objectives and the complex logistics required to define requirements and resource use (CRAB, boats, computers, office space, etc.). In turn, SandyDuck '97 became the largest coastal field experiment ever with participants from 18 universities; six Federal agencies; two private companies, and three foreign countries, conducting 30 separate experiments. Results of SandyDuck '97 are just now reaching publication.

One little recognized but important benefit of these experiments was the opportunity for interaction among the participants. The experiments brought together researchers that typically meet only at conferences perhaps once or twice a year. For an extended period of 1 to 6 months, these scientists and engineers, together with their students and technical support staff, shared space, resources, and ideas. In addition to deploying instruments and collecting data, meetings and seminars were held; hypotheses were proposed and discussed; abstracts and papers were written; and science was advanced. DUCK94 was so intense and interesting an experience, that it was highlighted in a chapter by Dean (1999). SandyDuck '97 received national recognition by being featured on the Cable News Network (CNN), the Weather Channel, and in USA Today.

SandyDuck was followed by SHOWEX, the Shoaling Waves Experiment, in the fall of 1999. SHOWEX was sponsored by the Office of Naval Research and designed to improve the scientific understanding of the properties and evolution of surface gravity waves typical of inner continental shelves up to the edge of the surf zone. The FRF provided logistic support for the shore-based operations including several surf zone components.

In addition to the major experiments, the FRF has also hosted a large number of smaller specialty experiments for users who benefit from the logistic support, field expertise of the staff, and available data. These studies, which have usually been supported by the Navy or Army, have covered a wide range of topics. These include atmospheric aerosols; mine detection and countermeasures; remote sensing ground truth; surveying techniques; ocean wave reflectance; wave growth and transformation; dune and marsh vegetation studies; and radar

Figure 9. DUCK94 primary cross-shore instrument array being serviced. Unlike during DUCK85 (Figure 8), to provide continuous coverage even during storms, sediment-transport measurements during DUCK94 and SandyDuck were made with in situ instruments

detection of waves and currents. These studies are always interesting because they present new challenges, broaden the FRF's logistic experience, and often introduce new state-of-the-art field instrumentation.

Impact on Research

The Field Research Facility has played a significant role in the advancement of nearshore science as evidenced by the number of publications pertaining to research conducted there. A recent compilation of bibliographic references indicates that more publications have been written describing observations obtained at Duck than for any other coastal facility worldwide. In addition to the hundreds of conference presentations given, approximately 150 journal articles, 108 reports, and 84 conference Proceedings papers have been published, and using FRF data by more than 200 authors representing 42 separate organizations and 16 different nationalities. Topics covered include acoustics, sandbar systems, beach cusps, bed forms, bottom boundary layers, coastal structures, directional spectra, edge waves, experiment summaries, equipment descriptions, facility guides, infragravity motions, morphodynamics, sediment transport, shear waves, surface gravity waves, swash processes, and wind-driven flows. A listing of these publications is available online at http://frf.usace.army.mil/biblio/pubs2.stm.

Many of these publications serve as primary references in the topics of nearshore oceanography and coastal engineering (several papers have been cited more than 40 times). Others stand as creative or innovative applications of technology towards resolving difficult research questions. For example, there have been a number of publications (including Birkemeier 1984; Lippmann and Holman 1993; Larson and Kraus 1994; Plant et al. 1999) pertaining to nearshore profile evolution data collected by the CRAB (Figure 10). Another significant series of publications relating to shear waves (Figure 11) can be traced to their observation by Oltman-Shay et al. (1989) during SUPERDUCK. Shear waves are generated by a shear instability of the mean longshore current. Similarly, over a dozen articles have been published establishing the usefulness of video (Figure 12) for making long-term, spatially extensive measurements of sand bar behavior (starting with Lippmann and Holman 1990) and beach profiles (e.g., Holman et al. 1991; Plant and Holman 1997; Stockdon and Holman

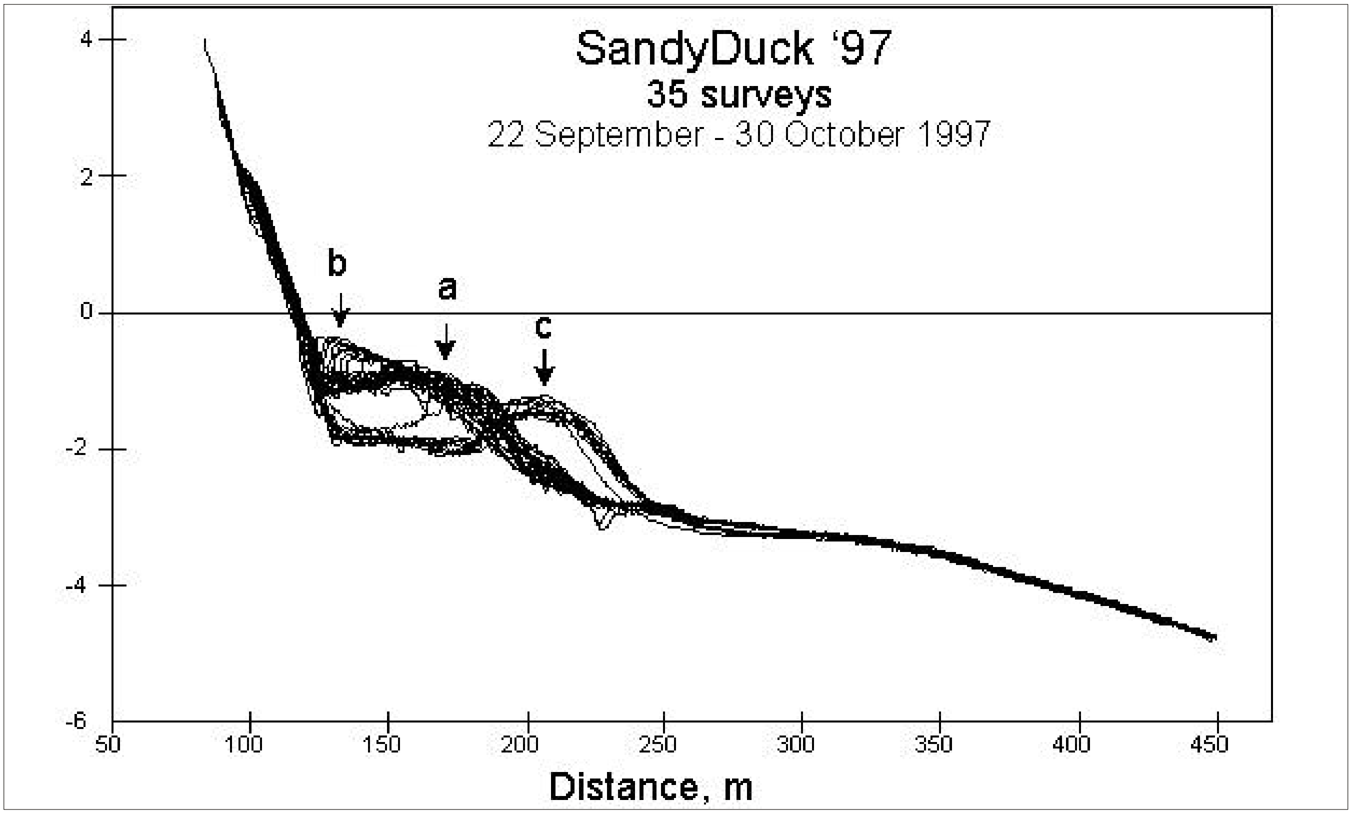

Figure 10. Envelope of cross-section surveys during the SandyDuck experiment showing large variations of bottom topography. During this period the sand bar was initially at location a, migrated onshore to location b, then moved offshore to location c during a passing storm

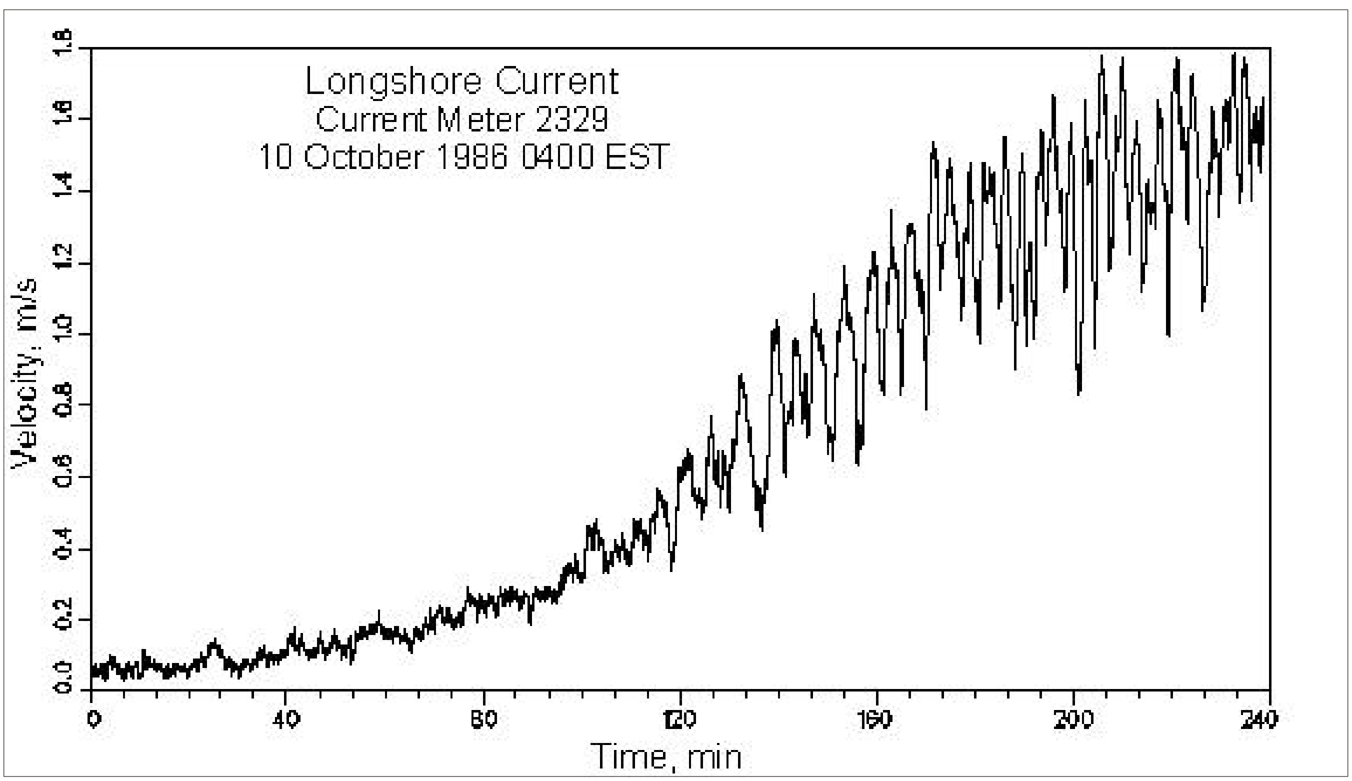

Figure 11. Evidence of shear waves found in 1986 during the SUPERDUCK experiment. Note the development of large-amplitude long-period wave forms after about 120 min, when the longshore velocity increased above 4 m/sec (after Hathaway et al. 1998)

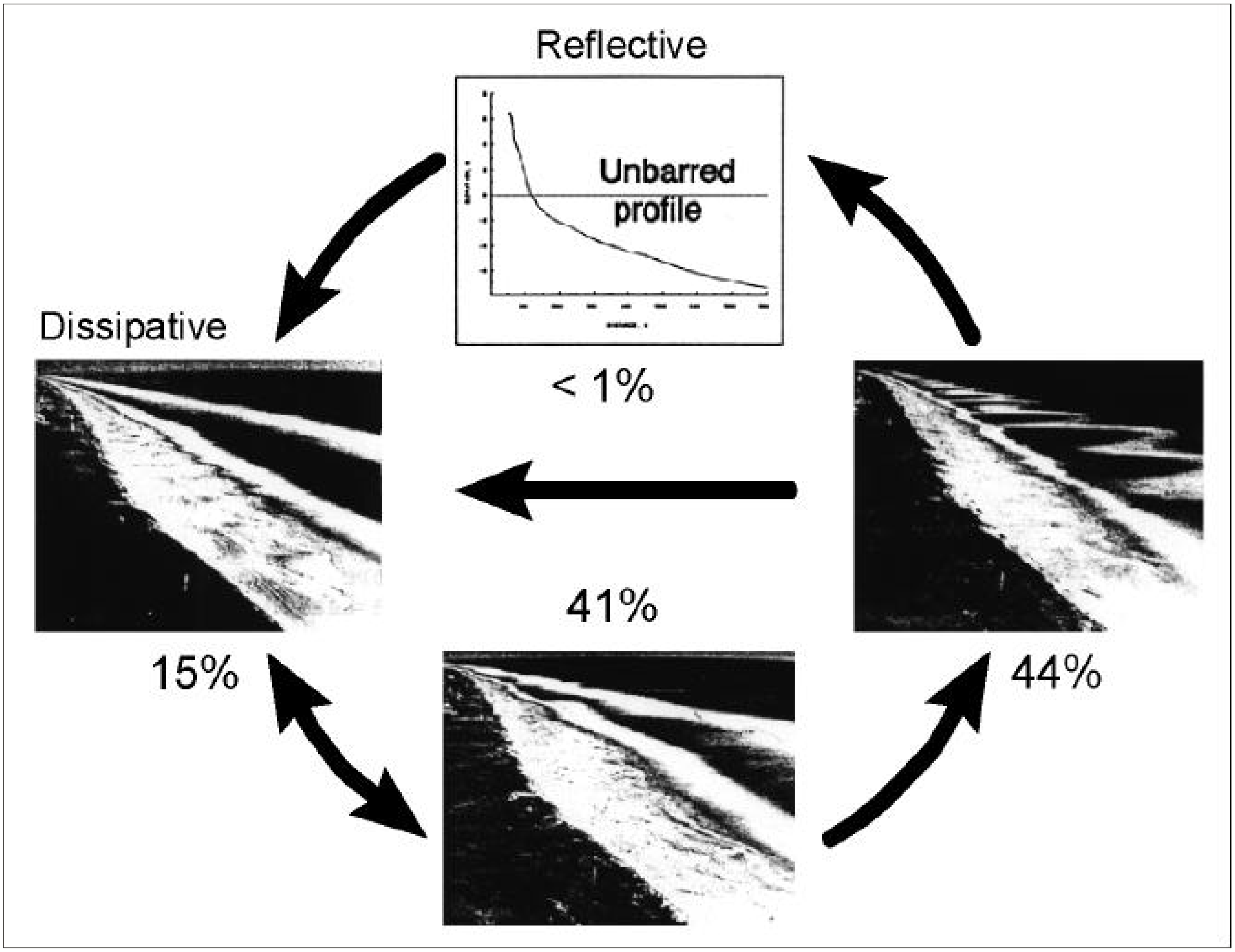

Figure 12. Diagram of beach states using time exposure video images modified from Lippmann and Holman (1990). Numbers indicate the percent of time that the nearshore morphology is unbarred, linear, mildly crescentic, or crescentic

2000). Other authors developed novel methods for using sonars to accurately monitor bottom bed forms (Gallagher et al. 1998b; Thornton et al. 1998).

The Duck location has served as an ideal site for the extension of these findings to other locales worldwide. The variability in waves, currents, and morphology at Duck has allowed hypotheses developed using data from the FRF to be validated elsewhere. For example, the fact that Duck experiences both reflective and dissipative conditions allowed the establishment of a relative scaling for infragravity motions with respect to offshore incident wave conditions (e.g., Holman and Sallenger 1985; Howd et al. 1991; Holland and Holman 1999). Interpretation of the extensive data collected during FRF experiments has also spurred the development and validation of models for alongshore momentum balances (Feddersen et al. 1998; Lentz et al. 1999), sand bar generation and migration (Sallenger et al. 1985; Holman and Sallenger 1993; Thornton et al. 1996; Gallagher et al. 1998a), wave energy transformation (Lippmann, Brookins, and Thornton 1996; Elgar et al. 1997), and the vertical structure of cross-shore currents (Haines and Sallenger 1994; Faria et al. 2000). There is little doubt that the existence of the FRF has resulted in publications that have extended our understanding of the complex interactions between hydrodynamic and morphodynamic processes.

Importantly, this research is leading to improved technology, procedures, and models for use by the Corps. For example, FRF data were used in the development and validation of the SBEACH (Larson and Kraus 1989) profile change model and GENESIS (Hanson and Kraus 1989) a shoreline change model. Corps Districts use software and survey procedures developed or tested at the FRF. Wave observations have contributed to more realistic wave modeling. Instrument tests and evaluations conducted at the FRF have led to more robust and reliable gauging at remote Corps sites. Video techniques developed at the FRF are being used in innovative ways to address unique Corps problems. Continued use of the Duck data set will raise the level of sophistication of the next generation of Corps nearshore numerical models.

A final, increasingly valuable aspect of FRF activities is the ongoing collection of long-time series of beach variability at a representative nearshore site. Only in the last decade has the existence and importance of interannual beach changes become apparent (Wijnberg and Terwindt 1995; Plant et al. 1999). Bathymetry and wave records from the FRF are one of only three long data records worldwide (Aarninkhof and Holman 1999; Wijnberg and Terwindt 1995) with which these phenomena can be studied.

Data Access

FRF data have always been accessible. For many years, the data were published in series of monthly preliminary data summaries and annual reports (Leffler et al. 1998). Association of the FRF with universities had an added benefit in 1994 when researchers from the Scripps Institution of Oceanography created the first FRF Web site to distribute information and data during DUCK94. The Web site quickly became the principle mechanism for distributing observations and video imagery in real time, along with historic data. Most FRF data are now available online including the major data sets from DELILAH and DUCK94. Printable versions of the monthly reports, climatalogical summaries of FRF data, descriptions of instruments, and information about the facilities, vehicles and equipment are also available. The FRF Web site (http://frf.usace.army.mil) has been very successful and currently averages 5,700 users per month.

The Web site also serves the public providing real-time ocean conditions and a “virtual” tour of the facility. Many visitors get an up-close look at the FRF by taking one of the well-attended summer tours or visiting with a group. The FRF is also a popular stop for coastal field trips along the Outer Banks for everyone from third graders to graduate students and science teachers.

Future Activities

Mason (1979) compiled a list of 29 potential studies to be conducted at the FRF. Many of these have now been accomplished, some more than once. Relevant among the remaining studies is the movement of nearshore placed material for beach nourishment, an experiment that is presently being discussed. Many topics not on the original list are now feasible to study owing to new instruments and technologies. Some subjects are wave breaking, sediment transport (to include size fractional rates), and the influence of currents combined with waves. Contributing technologies include acoustic current meters, digital video cameras, small rotary side-scan sonars, bottom-mounted acoustic altimeters, and new sediment transport sensors. High-resolution and spatially extensive remote sensing techniques are being developed which require verification with good ground truth data. These techniques, combined with the expertise of the FRF, will also be useful as the Corps’ research program shifts to focus on questions related to the regional management of sediment.

The role of the FRF continues to evolve. It will be part of the new Integrated Ocean Observing System developing under the auspices of the National Oceanographic Partnership Program (http://www.nopp.org) and the Ocean.US office (http://www.ocean.us.net). This program is helping to integrate the ocean research interests of 14 Federal agencies and recognizes the value of data from facilities like the FRF to support the general knowledge of the ocean along with providing the wide spatial observations required for regional and global ocean models. The 23-year-long FRF data set will allow new, climatic change questions to be addressed and the interannual variability in coastal dynamics and morphology to be studied. The national value of sites such as the FRF is being recognized (Woods Hole Oceanographic Institution 2000) and a new consortium of East Coast facilities is developing to share data and resources.

Epilogue

This paper has reviewed the capabilities and progress of the Field Research Facility, established by the U.S. Army Corps of Engineers in 1977 to support their coastal research requirements. Through the unique combination of facilities, vehicles, long-term measurements, staff expertise, and a large and energetic community of users, the original objectives of the FRF creators have been exceeded. If anything, the first 23 years of the FRF have shown that, although much has been explained, even more remains to be learned. Our experience has been that improvements in observations usually challenge our existing understanding and raises new questions to be answered. The process of discovery is incremental, not easily rushed, and is continuing in Duck, NC at the U.S. Army Corps of Engineers’ Field Research Facility.

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References

Aarninkhof, S., and Holman, R. A. (1999). “Monitoring the nearshore with video,” *Backscatter* 10(2), 8-11.

Baer, L., and Vincent, C. L. (1983). “Atlantic Remote-Sensing Land Ocean Experiment (ARSLOE) – Overview,” *IEEE Journal of Oceanic Engineering* 8(4), 201-205.

Bascom, W. N. (1987). "The Waves project, an illustrated letter to Morrough P. O'Brien," *Shore and Beach* 55(3-4), 25-30.

Birkemeier, W. A. (1984). "Time scales of nearshore profile change," *Proceedings of the 19th International Conference on Coastal Engineering,* ASCE, 1507-1521.

Birkemeier, W. A., and Mason, C. (1984). "The CRAB: A unique nearshore surveying vehicle," *Journal of Surveying Engineering* 110 (1), 1-7.

Birkemeier, W. A., Baron, C. F., Leffler, M. W., Hathaway, K. K., Miller, H. C., and Strider, J. B. (1989). "SUPERDUCK nearshore processes experiment: Data summary, CERC Field Research Facility," MP CERC-89-16, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Birkemeier, W. A., and Thornton, E. B. (1994). "The DUCK94 nearshore field experiment," *Proceedings of the Conference on Coastal Dynamics 94*, ASCE, 815-821.

Birkemeier, W. A., Donoghue, C., Long, C. E., Hathaway, K. K., and Baron, C. F. (1997). "The DELILAH nearshore experiment: Summary data report," TR-97-24, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Birkemeier, W. A., Long, C. E., and Hathaway, K. K. (1997). "DELILAH, DUCK94 & SandyDuck: Three nearshore experiments," *Proceedings of the 25th International Conference on Coastal Engineering*, ASCE, 4052-4065.

Bowen, A. J., and Inman, D. L. (1971). "Edge waves and crescentic bars," *Journal of Geophysical Research*, 76 (C36), 8662-8671.

Butman, C. A. (1994). "CoOP: Coastal Ocean Processes Study," *Sea Technology* 35(1), 44-49.

Crowson, R. A., Birkemeier, W. A., Klein, H. M., and Miller, H. C. (1988). "SUPERDUCK nearshore processes experiment: summary of studies, CERC Field Research Facility," TP CERC-88-12, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Dean, C. (1999). *Against the tide: The battle for America s beaches*. Columbia University Press, New York.

Elgar, S., Guza, R. T., Raubenheimer, B., Herbers, T. H. C., and Gallagher, E. L. (1997). "Spectral evolution of shoaling and breaking waves on a barred beach," *Journal of Geophysical Research* 102 (C7), 15797-15805.

Elgar, S., Guza, R. T., O'Reilly, W. C., Raubenheimer, B., and Herbers, T. H. C. (2001). "Wave energy and direction observed near a pier," *Journal of Waterways, Port, Coastal, and Ocean Engineering* 127(1), 2-6.

Faria, A. F. G., Thornton, E. B., Lippmann, T. C., and Stanton, T. P. (2000). "Undertow over a barred beach," *Journal of Geophysical Research* 105 (C7), 16999-17010.

Feddersen, F., Guza, R. T., Elgar, S., and Herbers, T. H. C. (1998). "Alongshore momentum balances in the nearshore," *Journal of Geophysical Research* 103 (C8), 15667-15676.

Gallagher, E. L., Elgar, S., and Guza, R. T. (1998a). "Observations of sand bar evolution on a natural beach," *Journal of Geophysical Research* 103 (C2), 3203-3215.

Gallagher, E. L., Elgar, S., and Thornton, E. B. (1998b). "Megaripple migration in a natural surf zone," *Nature* 394 (6689), 165-168.

Haines, J. W., and Sallenger, A. H. (1994). "Vertical structure of mean cross-shore currents across a barred surf zone," *Journal of Geophysical Research* 99 (C7), 14,223-14,242.

Hanson, H., and Kraus, N. C. (1989). "GENESIS: Generalized model for simulating shoreline change," TR CERC-89-19, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hathaway, K. K., Oltman-Shay, J. M., Howd, P. A., and Holman, R. A. (1998). "Infragravity waves in the nearshore zone," TR CHL-98-30, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Holland, K. T., and Holman, R. A. (1999). "Wavenumber-frequency structure of infragravity swash motions," *Journal of Geophysical Research* 104 (C6), 13,479-13,488.

Holland, K. T., and Puleo, J. A. (in preparation). "Variable swash motions associated with foreshore profile change," *Journal of Geophysical Research*.

Holman, R. A., Lippmann, T. C., O'Neill, P. V., and Hathaway, K. (1991). "Video estimation of subaerial beach profiles," *Marine Geology*, *97* (1-2), 225-231.

Holman, R. A., and Sallenger, A. H., Jr. (1985). "Setup and swash on a natural beach," *Journal of Geophysical Research* 90 (C1), 945-953.

Holman, R. A., and Sallenger, A. H., Jr. (1993). "Sand bar generation: A discussion of the Duck experiment series," *Journal of Coastal Research* SI 15, 76-92.

Howd, P. A., and Birkemeier, W. A. (1987). "Dynamics of morphology change during DUCK85," *Proceedings of the Coastal Sediments 87 Conference*, ASCE, 834-847.

Howd, P. A., Oltman-Shay, J., and Holman, R. A. (1991). "Wave variance partitioning in the trough of a barred beach," *Journal of Geophysical Research* 96 (C7), 12,781-12,795.

Larson, M., and Kraus, N. C. (1989). "SBEACH: Numerical model for simulating storm-induced beach change," TR CERC-89-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Larson, M., and Kraus, N. C. (1994). "Temporal and spatial scales of beach profile change, Duck, North

Carolina," *Marine Geology* 117 (1-4), 75-94.

Leffler, M. W., Baron, C. F., Scarborough, B. L., Hodges, P. R., and Townsend, C. R. (1998). "Annual data summary for 1995 CHL field research facility. Volume I: Main text and Appendixes A and B," Technical Report WES/TR /CHL-98-14-VOL-1, U.S. Army Engineer Waterways Experiment Station.

Lentz, S., Guza, R. T., Elgar, S., Feddersen, F., and Herbers, T. H. C. (1999). "Momentum balances on the North Carolina inner shelf," *Journal of Geophysical Research* 104 (C8), 18205-18226.

Lippmann, T. C., Brookins, A. H., and Thornton, E. B. (1996). "Wave energy transformation on natural profiles," *Coastal Engineering* 27 (1-2), 1-20.

Lippmann, T. C., and Holman, R. A. (1990). "The spatial and temporal variability of sand bar morphology," *Journal of Geophysical Research* 95 (C7), 11,575-11,590.

Lippmann, T. C., and Holman, R. A. (1993). "Episodic, non-stationary behavior of a two sand bar system at Duck, NC, USA," *Journal of Coastal Research SI* (15), 49-75.

Long, C. E., and Oltman-Shay, J. M. (1991). "Directional characteristics of waves in shallow water," Technical Report CERC-91-1, U.S. Army Engineers Waterways Experiment Station, Coastal and Hydraulics Laboratory, Vicksburg, MS.

Mason, C. (1979). "The Coastal Engineering Research Center's Field Research Facility at Duck, North Carolina," *Shore and Beach* 47(2), 13-16.

Mason, C., Sallenger, A. H., Holman, R. A., and Birkemeier, W. A. (1985). "DUCK82 - A coastal storm processes experiment," *Proceedings of the Coastal Engineering Conference*, ASCE, Houston, TX.

Mason, C., Birkemeier, W. A., and Howd, P. A. (1987). "An overview of DUCK85, a nearshore processes experiment," *Proceedings of the Coastal Sediments 87* Conference, ASCE.

Miller, H. C. (1980). "Instrumentation at CERC's Field Research Facility, Duck, North Carolina," Miscellaneous Report 80-8, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Miller, H. C., Birkemeier, W. A., and DeWall, A. E. (1983). "Effect of CERC research pier on nearshore processes," *Proceedings, Coastal Structures 83 Conference*, ASCE, 765-785.

Miller, H. C. (2000). "The sensor insertion system, an installation alternative at Duck, NC, USA," *Coastal Engineering Journal* 42(3), 273-294.

Moore, J. W., and Moore, D. P. (1991). "History of the Coastal Engineering Research Center," Volume I: WES Laboratory History Series, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Oltman-Shay, J., and Guza, R. T. (1987). "Infragravity edge wave observations on two California beaches," *Journal of Physical Oceanography, 17* (5), 644-663.

Oltman-Shay, J., Howd, P. A., and Birkemeier, W. A. (1989). "Shear instabilities of the mean longshore current: 2. Field observations," *Journal of Geophysical Research* 94 (C12), 18,031-18,042.

Plant, N. G., and Holman, R. A. (1997). "Intertidal beach profile estimation using video images," *Marine Geology* 140 (1-2), 1-24.

Plant, N. G., Holman, R. A., Freilich, M. H., and Birkemeier, W. A. (1999). "A simple model for interannual sandbar behavior," *Journal of Geophysical Research* 104 (C7), 15755-15776.

Sallenger, A. H., Jr., Holman, R. A., and Birkemeier, W. A. (1985). "Storm-induced response of a nearshore bar system," *Marine Geology* 64 (3-4), 237-257.

Stockdon, H. F., and Holman, R. A. (2000). "Estimation of wave phase speed and nearshore bathymetry from video imagery," *Journal of Geophysical Research* 105 (C9), 22015-22033.

Thornton, E. B., Humiston, R. T., and Birkemeier, W. (1996). "Bar/trough generation on a natural beach," *Journal of Geophysical Research* 101 (C5), 12097-12110.

Thornton, E. B., Swayne, J. L., and Dingler, J. R. (1998). "Small-scale morphology across the surf zone," *Marine Geology* 145 (3-4), 173-196.

Wijnberg, K. M., and Terwindt, J. H. J. (1995). "Extracting decadal morphological behavior from high resolution, long-term bathymetric surveys along the Holland coast using eigenfunction analysis," *Marine Geology* 126, 301-330.

Woody, C. E., Dagnall, R., Michelena, E., McGehee, D., Bichner, G., and Mero, T. (1997). "Oceanographic test facility at Duck Pier, NC." *Proceedings of Oceans 97*, Marine Technology Society, IEEE, 1094-1098.

Woods Hole Oceanographic Institution. (2000). "Ocean observatories," *Oceanus*, 42(1). 33 p.